Flow Through the Straits of the Philippine Archipelago Simulated by Global HYCOM and EAS NCOM

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LONG-TERM GOALS

We plan to collaborate with other DRI participants to better evaluate and understand the dynamics seen in observations and model results within the Philippine Archipelago, a strategic region with numerous straits. The model results will come from the .08° and .04° global HYbrid Coordinate Ocean Model (HYCOM) and a .088° East Asian Seas (EAS) Navy Coastal Ocean Model (NCOM), the .04° global HYCOM and some finer nests starting in FY09, the others from the outset.

OBJECTIVES

Objectives for our DRI participation are (1) high resolution simulations (with and without tides; with and without data assimilation) which provide a larger scale context for the observations, (2) model-data comparisons with the measurements, (3) studies of observational representativeness in measuring transports through straits, (4) investigation of non-tidal and tidal (barotropic and internal) influences on specific sub-regions of interest, especially where measurements are available, and (5) provide boundary conditions for nested models.

APPROACH

Ocean models: HYCOM: Traditional ocean models use a single coordinate type to represent the vertical, but no single approach is optimal for the global ocean. Isopycnal (density tracking) layers are best in the deep stratified ocean, z-levels (constant fixed depths) provide high vertical resolution in the mixed layer, and σ-levels (terrain-following) are often the best choice in coastal regions. The generalized vertical coordinate in HYCOM allows a combination of all three types (and others), and it dynamically chooses the optimal distribution at every time step via the layered continuity equation.

NCOM uses σ-levels when the depth is shallower than 137 m and z-levels, optionally with partial cell topography, elsewhere.

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Both models use a C-grid, have scalable, portable computer codes that run efficiently on available DoD High Performance Computing (HPC) platforms, and have a data assimilation capability. NCOM runs with tides. These have been added to HYCOM and results from the first 1/12° global simulation with tides and atmospheric forcing are currently being analyzed.

Task (1) (corresponding to the list in the objectives) High resolution ocean model simulations: HYCOM will be run globally with .08° (9 km equatorial) and .04° (4 km equatorial) resolution, the latter starting in FY09. These will be run largely under the sponsorship of partnering and related projects (see Related Projects below). The simulations will be run with high frequency climatological forcing and will be run interannually at least over the time frame of the International Nusantara STratification ANd Transport (INSTANT) and DRI data sets. Simulations will be run with and without tides, and with and without data assimilation.

The .088° EAS NCOM (17°S-52°N, 98°E-158°E) has been running in real-time with tides and data assimilation since October 2003. It receives boundary conditions from .176° (20 km) equatorial resolution global NCOM (with data assimilation but no tides).

Nested models of the Philippine Seas using HYCOM and NCOM are also planned. Both models already have a robust nesting capability. During the first 3 years the nests would have 3 km resolution and during years 4-5 a Philippine Seas nest in .04° global HYCOM would have 1.5 km resolution. The nested models will be very useful (1) for investigating the impact of resolution on other aspects of the simulations, (2) as boundary conditions for even higher resolution nested models of Philippine Seas subregions run by other DRI participants, and (3) for data representativeness studies. Even same resolution nests will be useful in studying the impacts of tides, different vertical mixing schemes and parameter choices, and data assimilation on other aspects of the Philippine Seas circulation.

Task (2) Model-data comparison studies: The model-data comparisons will be used to evaluate and improve the models and to help interpret the data. Data that resolve tidal frequencies, and measure straits transports, the vertical structure of the water column, and the nature of its variability will be particularly useful. Measures of year-long means and seasonal variability will also be valuable. Model output will be archived at measurement locations with sufficient temporal resolution for tides. Measurements used in conjunction with models will be vital in studying the roles that tides and other processes play in determining transports though straits and the vertical structure of the water column. Timely access to DRI data will greatly facilitate this process and opportunities for joint publications with other DRI participants are highly desirable, particularly in years 3-5.

Task (3) Studies of data representiveness: All of the models listed in Task (1) can be very useful in assessing the ability of DRI observational arrays to measure integral properties, such as straits transport (both in terms of spatial coverage and length of record), particularly if they perform well in the model-data comparisons (Task 2). They can also be used in estimating appropriate corrections in data analyses. Doing this using a suite of model simulations, rather than just one, and picking models that best match the data should improve the quality of corrections and enhance confidence in the results.

Task (4) Study the interaction of tidal and non-tidal processes in subregions of DRI interest: The Philippine Seas form a region where large amplitude external and internal tides may have a significant impact on the non-tidal circulation and water mass structure. We are particularly interested in

collaborative studies and joint publications on related topics with other DRI participants in subregions of DRI interest.

Task (5) Provide boundary conditions for nested models of other DRI participants: HYCOM and NCOM will be used to provide boundary conditions to nested models of other DRI participants. The boundary conditions can have resolution as fine as 3 km during years 1-3 and as fine as 1 km during years 4-5. Advance coordination would be needed to make sure the required time period was archived at the temporal resolution and locations needed. We are also interested in model inter-comparisons to investigate the impact of model resolution and design on the simulation of processes in the vicinity of straits.

WORK COMPLETED

Output from .08° global HYCOM and .088° EAS NCOM was used to aid mission planning for the Joint (December 2007) and 1st Intense Observing Period (IOP) (January 2008) cruises. Results from non-assimilative climatologically-forced and assimilative interannually-forced simulations of the Philippine Seas were forwarded to the observational team with emphasis on straits where intensive sampling was planned. These included cross-sections of the temperature, salinity and velocity as well as time series of transport through the inflow and outflow straits. Output from both real-time systems was posted on the NRL web pages for guidance.

The real-time .088° EAS NCOM system was moved to the IBM Power 5+ at the Naval Oceanographic Office (NAVOCEANO) Major Shared Resource Center. This was required because the computer (IBM Power 4+) on which it was run had been decommissioned. NAVOCEANO has decided not to make this an operational system, but has agreed to keep it running in real-time for the duration of the DRI.

Two major .08° global HYCOM simulations were integrated. The first (HYCOM-B) was a non-assimilative simulation using 3-hourly January 2003 through June 2008 0.5° Navy Operational Global Atmospheric Prediction System (NOGAPS) forcing. It is a near twin to an existing experiment (HYCOM-A) except it was started from a spin-up using different climatological forcing and it used the K-profile parameterization (KPP) mixed layer sub-model rather than the Goddard Institute for Space Studies (GISS) sub-model. The second simulation (HYCOM-BT) is a twin of HYCOM-B except that it additionally included forcing using the eight largest tidal constituents (M2, S2, K1, O1, N2, P1, K2, Q1). This is the first high horizontal/vertical resolution global ocean model to be run with standard atmospheric forcing and tides. These simulations were analyzed in the DRI region of interest, compared against available observations and reported on at the August 2008 PhilEx DRI meeting in Monterey, CA. Output from the two HYCOM simulations was also used to aid mission planning for the 2nd IOP (Winter 2008), especially with regard to the impact of tides on the mean circulation.

Similarly, .088° EAS NCOM was compared to observations and also reported on at the Monterey and Manila, Philippines (May 2008) project meetings. Observational sea surface temperature (SST) and sea surface salinity (SSS) at the various locations along the ship tracks from the Joint Cruise were obtained from the Wiki server. Comparisons were also made to CTD data taken on this cruise.

A 2-km relocatable NCOM of the Philippines area, including the Sulu Sea, was set-up and integrated. EAS NCOM values are used as boundary conditions for the relocatable simulations. Tides are included in EAS NCOM thus the relocatable model has tidal forcing at the boundaries. The relocatable model

was tested over the December 2007 time period and two simulations have been completed. One used 0.5° NOGAPS forcing while the other used 9 km Coupled Ocean Atmosphere Mesoscale Prediction System-On Scene (COAMPS-OS) atmospheric fields.

In conjunction with the 6.1 Indonesian Throughflow project (see Related Projects below), an examination of the model sill depths in relation to observations at some key passageways was undertaken for global HYCOM. In general, model sill depths are shallower than observed because a 9-point smoothing was applied to the topography in an effort to reduce numerical noise associated with small bathymetric features. While the focus of this topography analysis was on the Indonesian Seas, the work did expand far enough north that Sibutu Passage (connection between the Sulu and Sulawesi Seas), Dipolog Strait (connection between the Sulu and Bohol Seas) and Surigao Strait (the connection between the Pacific Ocean and the Bohol Sea) were modified with the Smith and Sandwell (1997) topography. Unfortunately, the Mindoro Strait (connection between the South China and the Sulu Seas) was not modified. We repeated two years of an existing climatologically forced simulation with this new topography to assess the impact.

Boundary conditions from the real-time data assimilative .08° global HYCOM system were extracted and provided to the Rutgers group running the Regional Ocean Modeling System (ROMS). These included hindcasts five days in arrears, the nowcast and then up to a four day forecast. In addition, atmospheric forcing (wind stress, heat fluxes and precipitation) from the 0.5° NOGAPS was provided. These were the same fields used to force global HYCOM.

RESULTS

The two .08° global HYCOM simulations (with [HYCOM-BT] and without tides [HYCOM-B]) give us a unique opportunity to study the impacts of tidal forcing on the circulation and vertical structure of the water column. As illustrated by the imagery in Figure 1, internal tides can have a strong surface signature in the interior Philippines seas. While not contemporaneous, HYCOM-BT has a clear representation of this surface signal that is generated in the same location and further indicates that internal tides are ubiquitous in the DRI regions of interest. The speed of the simulated internal tides (2.5 m/s) in the Sulu Sea is also similar to the observations (~2 m/s). Martin et al. (2006) found well defined beams of internal tides with amplitudes of ~60 m and wavelengths of 50 to 100 km propagating away from topographic source regions, reminiscent of the features observed in the simulation. Theoretical work by St. Laurent and Garrett (2002) suggests that these beams are primarily low vertical mode waves capable of propagating for distances of O(1000 km) with dissipation occurring due to critical slope interactions and bottom scattering causing enhanced mixing near the bottom.

Preliminary analysis indicates the internal tides have an impact over the entire depth of the water column, as a comparison with the PhilEx observations shows in Figure 2. Zonal and meridional velocity from an Acoustic Doppler Current Profiler (ADCP) in southern Mindoro Strait deployed during the Exploratory Cruise (June-July 2007) and recovered during the Joint Cruise (December 2007) indicate intensified flow in the bottom 100 m of the water column. Simulation HYCOM-B has no signature of this bottom intensification whereas it is clearly evident in simulation HYCOM-BT suggesting that tidal forcing has a significant impact on the vertical structure of the water column in Mindoro Strait. A time series of observed velocity at this location indicates the bottom flow was strong and persistent over the deployment period; a similar analysis from HYCOM-BT again shows the same bottom intensification, but the signal is not as persistent as the observations indicate (not shown).

A comparison of HYCOM-B and HYCOM-BT also indicates that tidal forcing can have an impact on the mean circulation, especially in some sub-basins where perhaps tidal resonance is important. Ship mounted ADCP velocity measurements taken during the Joint and 1st IOP Cruises indicated near surface (25-55 m) cyclonic and anti-cyclonic gyres in the western and eastern basins of the Bohol Sea, respectively (Figure 3). The same circulation pattern is seen in HYCOM-BT while HYCOM-B simulates northeast to southwest flow along the northern extreme of this semi-enclosed sea.

SST and SSS measurements during the Joint Cruise were compared to .088° EAS NCOM. Simulated values were interpolated to the time and location of the observed values. Figure 4 shows the difference between the simulated and observed data. Each location is marked with a dot colored by the simulated minus observed difference. The green and blue values indicate differences of 0.5°C or less. The table below contains composite statistics. The standard deviation of the model SSS is much smaller than observed because of SSS relaxation to climatology. Comparison between CTD data and EAS NCOM has just begun. Initial results indicate a simulated near surface (0-100 m) cold bias and a warm bias at mid-depths (100 to 200 m) on the order of 0.5°-1.0°C. There is fairly good agreement deeper in the water column.

	$Mean_{obs}$	$Mean_{mod}$	RMSE	σ_{obs}	σ_{mod}	Correlation
SST (°C)	27.2	27.8	0.4	0.4	0.5	0.6
SSS (PSU)	33.2	34.1	0.5	1.9	0.2	0.3

The 2-km relocatable NCOM test simulations show that the COAMPS-OS forced run yields cooler surface temperatures than the relocatable NCOM simulation with NOGAPS forcing or the .088° EAS NCOM integration. A known deficiency in COAMPS WESTPAC is low solar radiation near the equator due to too much cloud cover. It appears that the COAMPS-OS version used to force relocatable NCOM has the same problem. There may be parameter adjustments that can be made to the COAMPS-OS version to bring the cloud cover and thus solar radiation values into a more accurate range and this needs to be examined.

The impact of the topography modification was assessed by examining the transport through the key passages of the Philippines. Unfortunately, there are no definitive transport observations and thus the analysis is somewhat subjective. A significant change to the topography was a net shallowing of the Sulu Sea outflow at Sibutu Passage. This had an overall impact of reducing the South China Sea – Sulu Sea – Sulawesi Sea transport to 2.6 Sverdrups. Given the observed sill depth and cross-sectional area of this strait, this value seems more realistic than the simulated 3.7 Sverdrups before the topography modification.

IMPACT/APPLICATIONS

Comparison of the 1/12° global HYCOM simulations with and without tides led to the significant discovery of a strong tidal impact on the mean circulation within the Philippine Archipelago. This impact was seen throughout the vertical extent of the water column. Neither the DRI observationalists nor the modelers anticipated these results. No prior cruise planning was oriented toward the investigation of the impact of tides until this was reported at the August 2008 project meeting.

Output from .08° global HYCOM and .088° EAS NCOM also provided the larger scale context of the circulation in the Philippine Seas and real-time nowcast and forecast output from data-assimilative .08° global HYCOM was used as boundary conditions for a real-time regional ROMS system run by the group at Rutgers.

TRANSITIONS

Global NCOM is operational at NAVOCEANO while .088° EAS NCOM and .08° global HYCOM are running in real time. Global HYCOM was transitioned to NAVOCEANO at the end of FY08 and will go through operational testing in FY09. It received 6.4 SPAWAR funding (see below) for evaluation/validation. NAVOCEANO made the decision not to make EAS NCOM an operational product, but the system will continue to run in real-time for the duration of this DRI, hence the need to move it to a new computer as noted in the 'Work Completed' section above.

RELATED PROJECTS

As partnering funding, we would support related Indonesian/Philippines Seas work using two existing 6.1 NRL Base projects: "Global remote littoral forcing via deep water pathways" (H. Hurlburt, PI) and "Dynamics of the Indonesian throughflow (ITF) and its remote impact" (E.J. Metzger, PI). Related projects supporting global HYCOM would also substantially benefit this DRI project. These include the multi-institutional effort to develop a next generation eddy-resolving global ocean prediction system using HYCOM. This effort was supported by the FY04-08 NOPP project, "U.S. GODAE: Global Ocean Prediction with the HYbrid Coordinate Ocean Model (HYCOM)" (http://www.hycom.org) (H. Hurlburt, NRL PI) and a related existing 6.4 project "Large Scale Prediction" (E.J. Metzger, PI).

The computational effort will be strongly supported by DoD HPC Challenge and non-challenge grants of computer time. In FY08, .08° global HYCOM (without tides) ran under an FY05-08 DoD HPC Challenge grant. The tidally forced HYCOM simulation was part of an HPC Capability Application Project grant of computer time. The nested models were run under NRL grants of non-challenge HPC time. The .08° global HYCOM is very computationally expensive to run, but the available computer power increases every year and we will be able to run a limited number of .08° global HYCOM simulations including tides with NRL non-challenge HPC time. Development of tides within .08° and .04° global HYCOM will come under a new FY09-11 DoD HPC Challenge grant.

REFERENCES

Martin, J. P., D. L. Rudnick and R. Pinkel, 2006. Spatially broad observations of internal waves in the upper ocean at the Hawaiian Ridge. *J. Phys. Oceanogr.*, **36**, 1085-1103.

Smith, W.H.F. and D.T. Sandwell, 1997: Global seafloor topography from satellite altimetry and ship depth soundings. *Science*, **277**, 1957-1962.

St. Laurent, L. and C. Garrett, 2002. The role of internal tides in mixing the deep ocean. *J. Phys. Oceanogr.*, **32**, 2882-2899.

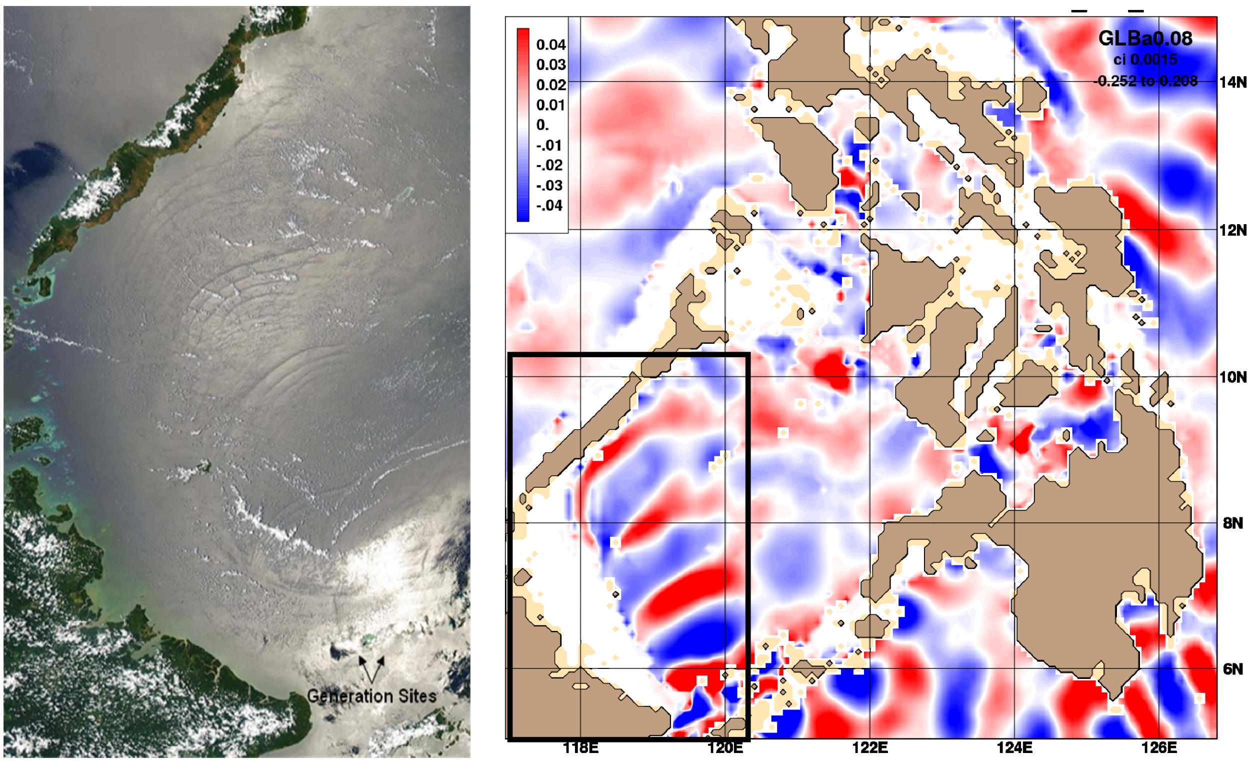

Figure 1: (left) MODIS true color image on 8 April 2003 of the western Sulu Sea. Note the sea surface height (SSH) signature of the internal tides that are generated near Sibutu Passage and propagate at speeds of ~2 m/s with internal amplitudes up to 90 m. (right) Steric SSH (in meters) anomaly from the 25-hour average centered on 15 May 2004 12Z from 1/12° global HYCOM with tidal forcing (HYCOM-BT) for the interior Philippine's seas. The black box outlines the region of the MODIS image. While not contemporaneous, global HYCOM has a similar SSH signature of the internal tides. Note also the strong internal tide signatures in Mindoro Strait and the Bohol Sea, both focus areas for the Intense Observing Period cruises.

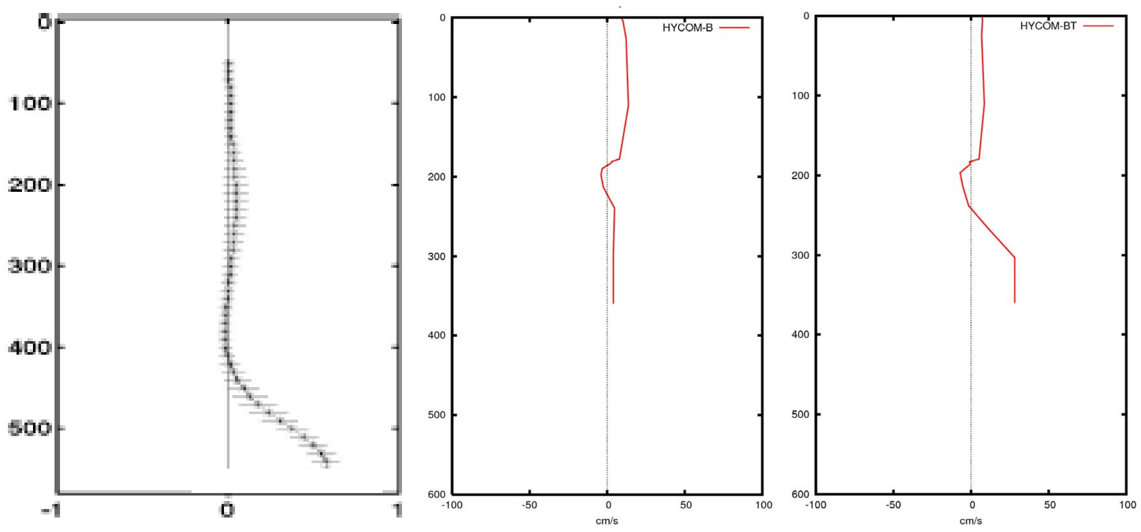

Figure 2: Zonal velocity (m/s) at the Panay ADCP mooring (11°16.6' N; 121°55.4' E) averaged over the time period June 2007 – December 2007 (left) (from J. Sprintall, Scripps Institution of Oceanography), from simulation HYCOM-B (middle) and simulation HYCOM-BT (right). Units of the simulated profiles are cm/s. The model topography is not as deep as the actual mooring because a 9-pt smoother was applied in order to reduce numerical noise.

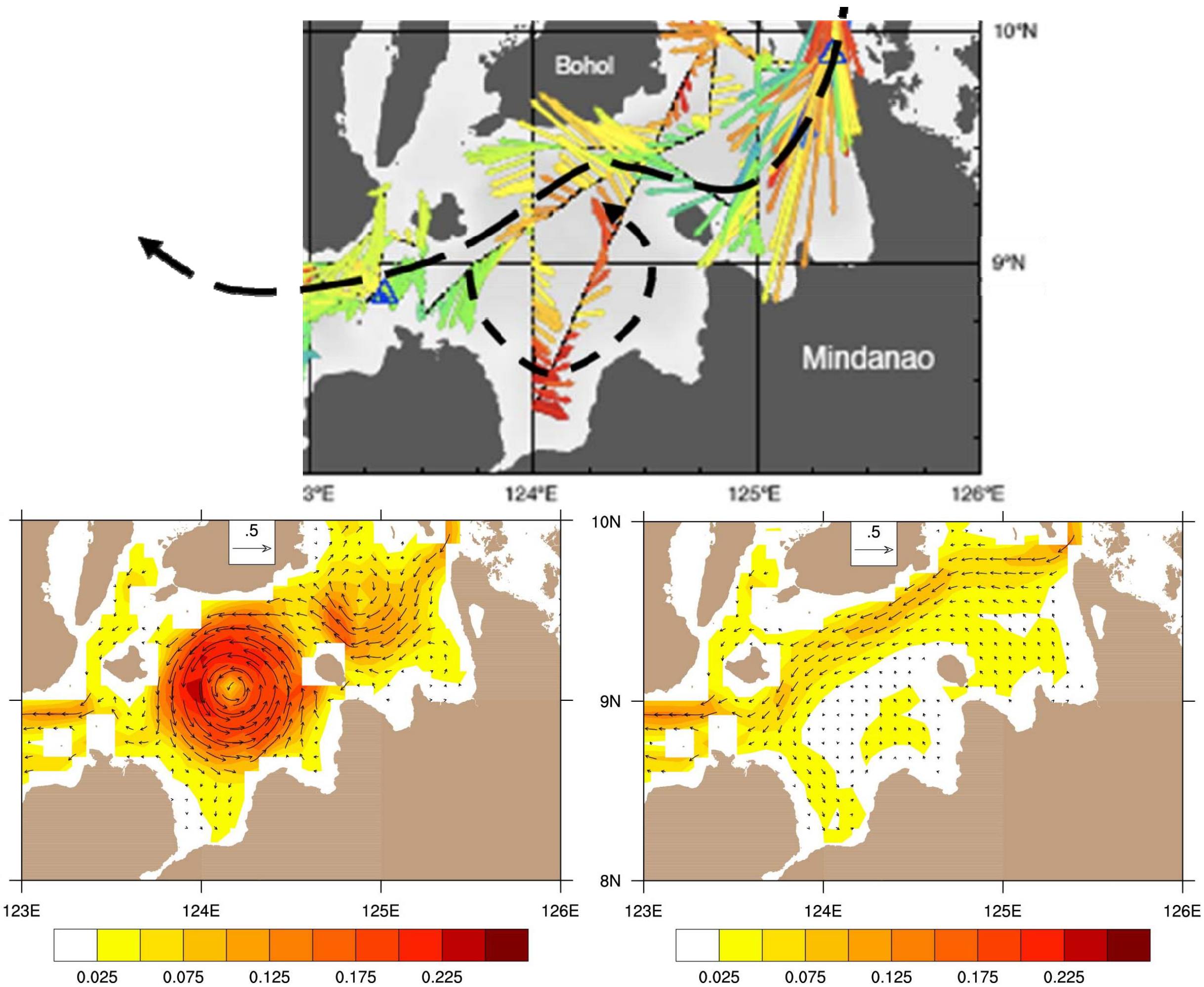

Figure 3: Regional IOP January 2008 hull mounted ADCP velocity vectors averaged over the depth range 25-55 m and color coded by sea surface temperature (SST) for the Bohol Sea (top) and velocity vectors at 50 m overlaid on color contours of speed (m/s) from HYCOM-BT (bottom left) and from HYCOM-B (bottom right). Simulated results are a January 2008 mean. Note the cyclonic and anti-cyclonic circulations in the western and eastern basins, respectively, in both the observations and the simulation with tidal forcing. While the Regional IOP 2008 is quasi-synoptic, similar gyre circulations were seen during other PhilEx DRI cruises and are persistent in HYCOM-BT.

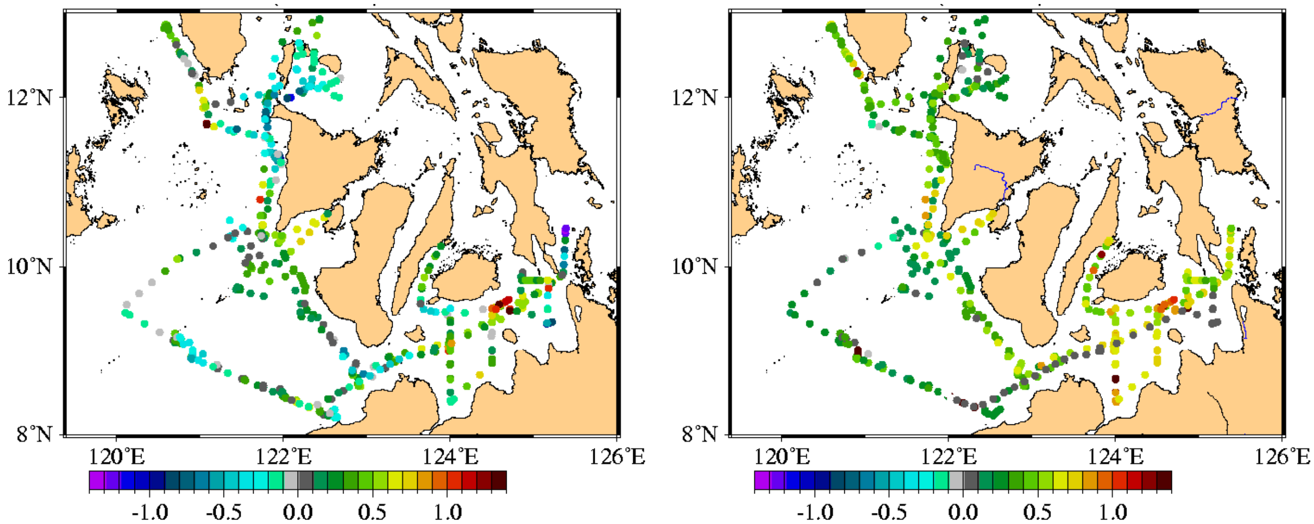

Figure 4: Simulated .088° EAS NCOM SST (left) and SSS (right) minus observations taken during the December 2007 Joint Cruise. The differences are computed hourly. Gray shades indicate SST (SSS) differences less than 0.1°C (0.1 PSU).